LABORATORY AND FIELD INVESTIGATIONS OF EPPLEY RADIATION SENSORS

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ABSTRACT

More precise radiation measurements in the Antarctic are required for studies designed to assess the radiation and heat budgets of that area. These requirements inspired the present investigation which is aimed at the experimental determination of certain of the instrumental characteristics and their consequences. Laboratory investigations of a group of Eppley pyranometers verifies previous findings that the temperature response is a unique characteristic of each instrument which can produce radiation-values 14 percent too high under the extreme Antarctic temperature conditions and differences between instruments at the same temperature of 3 to 8 percent. Tests made on the effect of inverting the pyranometer for the measurement of reflected solar radiation show that the instrument sensitivity decreases by 4 to 6 percent in this position. A test on one normal incidence pyrheliometer indicates virtually no temperature effect. Weather Bureau calibrations of several pyrheliometers give results in excellent agreement with the calibrations performed by Eppley Laboratory. Field shade calibrations and simultaneous exposure comparisons of a group of Eppley pyranometers at the South Pole indicate that the computation of the total solar radiation should probably be made using separate direct and diffuse calibration factors for the pyranometers.

1. INTRODUCTION

Eppley pyranometers and pyrheliometers have been used by the Weather Bureau in its Antarctic research program nearly continuously since 1957; see for example Hanson [6]. The pyranometer has certain characteristics which result in large systematic errors when the instrument is exposed to the extreme conditions of the Antarctic. Two sources of error are exposure to temperatures 50° to 110° F. lower than calibration temperature, and low solar angles. These factors can result in radiation data errors in excess of 10 percent. Another error results from use of the pyranometer in an inverted position. All these effects need to be known and considered if the resulting radiation data are to be useful. For example, failure to correct for the temperature and inversion errors in the determination of the solar radiation budget could result in the net radiation being calculated as positive (net gain for the surface) rather than negative.

The object of this paper is to present the results of the various experiments and to detail the magnitudes of the several instrumental errors.

2. INSTRUMENTATION

The Eppley normal incidence pyrheliometer and the horizontal incidence pyranometer are sufficiently well known (see for example CSAGI [2]) that additional description is unnecessary. Except where noted, the pyranometers discussed in this study are 50-junction type with sensitivities near 7 to 8 mv./(ly. min.$^{-1}$). Brief mention is made in the inversion study of another model Eppley pyranometer which utilizes double ground glass hemispheres, a blackened silver receiving surface, and a temperature compensated circuit. Further description of this type of pyranometer is given by Marchgraber and Armstrong [11].

3. TEMPERATURE RESPONSE TESTS

There has been considerable discussion about the temperature response of the pyranometer and its effect on the accuracy of the data. Despite the conclusive evidence presented by various investigators, many users including the U.S. Weather Bureau do not take account of this potentially large and variable error in reduction of their pyranometer data. An exception to this are the Antarctic radiation data published by the Weather Bureau [13]. All the investigators including MacDonald [8], [9], Fuquay and Buettner [5], Latimer [7], and Eppley Laboratory [3], agree as to the relative effect of temperature on the sensitivity of the pyranometer. The available sources on the temperature response of the pyrheliometer, however, do not agree. MacDonald [10] found no significant temperature effect, while Eppley Laboratory [3] indicates a large temperature coefficient of -0.11 percent/°F.

Table 1 summarizes the available pyranometer tem-

TABLE 1.—*Pyranometer temperature response*

Investigator	Number tested	Temperature range (°F.)	Temperature coefficient (percent/°F.)	
			Range	Mean
MacDonald [8]	7	−40 to +120	−0.028 to −0.103	−0.048
MacDonald [9]	14	−70 to +80		−0.129
Latimer [7]	28	−20 to +100	−0.027 to −0.11	−0.072
Spitzer [12]	?	−4 to +104	−0.03 to −0.06	−0.045
Eppley Lab. [3]	?	−58 to +104	−0.056 to −0.083	(−0.070)

perature response information. From the data of table 1, it may be surmised that there is considerable variation in response between instruments. This is readily evident in the curves published by MacDonald [8] where the response at °0 F. is 4.1 percent greater for instrument 1973 than for instrument 1221.

From the available evidence it appeared important to determine temperature response information for each radiation instrument used by the Weather Bureau in its Antarctic solar radiation program.

APPARATUS AND TECHNIQUE

The experiments discussed here were performed at the Weather Bureau in August and October 1963. The technique was basically that employed by MacDonald [8] with the major difference that in our investigation the instruments being tested were placed in a horizontal rather than a vertical position. The pyranometers were tested in pairs and the pyrheliometer separately. A test run lasted from 8 to 12 hr. and the operating temperatures were between +80° and −90° F.

The basic components of the test apparatus were a cold box which used dry ice as the coolant, an incandescent lamp for the radiation source, and two recorders to monitor the pyranometer and photocell outputs and the box and pyranometer temperatures. The instruments were mounted horizontally in the bottom of the cold chamber with thermocouples attached to the base and glass envelope of one of the pyranometers. The lamp was mounted outside and illuminated the pyranometers through a window in the top of the box. The lamp voltage was controlled and stabilized by a rheostat and a voltage regulator and monitored with a precision voltmeter. A photovoltaic cell mounted on the outside of the window facing the pyranometers received the radiation reflected from the cold chamber and was used to detect any changes in illumination.

To begin the test, the air in the box was cooled to its lowest temperature, usually near −90° F. The air temperature in the chamber was then raised by approximately equal increments of 25° to 35° F. until the highest temperature, near 75° to 80° F., was reached. If time permitted, the procedure was repeated in reverse until the box temperature was again near −90° F. At each temperature point where data were collected the temperature was stabilized (±2° F.) for about 15 min. It generally required about 45 min. to go from one temperature point to the next. The long stabilization time is required to avoid the effects of overshoot caused by the large and rapid temperature change, as discussed by MacDonald [8].

The recorded data were analyzed by comparing the pyranometer or pyrheliometer output at each temperature point with the output at the highest temperature attained. The results were graphed and a response curve based on 100 percent response at +80° F. was obtained.

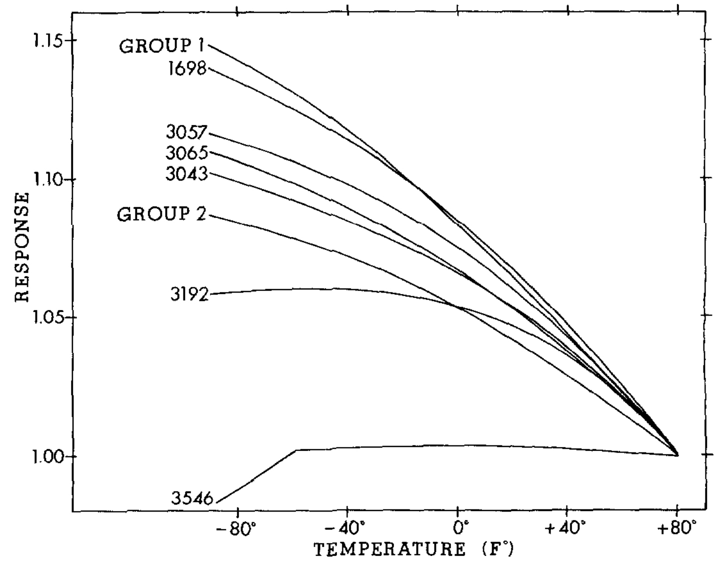

FIGURE 1.—Variation of instrument response with temperature.

TEST RESULTS

Eppley normal incidence No. 3546 was the only pyrheliometer tested in the cold box. The response curve is presented in figure 1. This instrument showed unusual stability both over the temperature range and during the rapid temperature changes used in the test. The only significant departure from 100 percent response occurs at the coldest point, −88° F. These results are in agreement with the unpublished findings of MacDonald [10].

Tests were performed on 11 pyranometers and the response curves are presented in figure 1. The response values are used to correct radiation data by dividing the radiation values (ly./min.) by the response figure.

Several of the pyranometers had response curves sufficiently similar that the individual curves could be replaced by a group curve. Two such groups resulted and aer represented in figure 1 by group curve 1 composed of pyranometers Nos. 3064, 3070, and 3072, and by group curve 2 composed of instruments No. 3058, 4266, and 4267. The group 1 curve was obtained from eight tests unevenly distributed among the three pyranometers. Group 2 curve was based on a single run on each of the three instruments. Variance tests applied to these data indicated that, within 99 percent confidence limits, the pyranometers within each group could have the common curve.

Figure 1 contains the curves for the other pyranometers tested and illustrates the large differences that can be expected from a random selection of instruments. The response curve for No. 3192 is unique in that it reaches maximum response at −55° F. with the response decreasing at lower temperatures. Two runs were obtained for this instrument with identical results. MacDonald [8] presents a similarly shaped curve although the reversal point was at 0° F. for the instrument he tested.

In general, the results of our tests agree with those of the other investigators. For comparison with the data in table 1, the portions of the curves of figure 1 between +20° and +80° F. give temperature coefficients between −0.070 and −0.108 percent/°F. with the average for the 11 pyranometers being −0.093 percent/°F. With the variability between instruments as evidenced in this and earlier studies, it seems important to define the temperature response for each pyranometer. Utilizing individual pyranometer response information would allow direct comparison of data from stations having markedly different temperature regimes as well as comparison between summer and winter measurements at stations having large annual temperature variations. From the response curves of figure 1, it is evident that errors as large as 8 to 10 percent are possible if one were to compare uncorrected winter solar radiation data from Florida with data from Minnesota, for example. Latitudinal and seasonal variations are minimized when the pyranometer temperature effect is disregarded.

4. INVERSION EFFECT

The Antarctic radiation program includes measurement of the reflected short-wave radiation obtained with an Eppley pyranometer in an inverted position. The field installation includes a concentric ring to shield the sensor from the direct solar beam and the exposure is from a height of about 15 ft. MacDonald [8] and Eppley Laboratory [3] have indicated that there is no significant effect when the pyranometer is inverted. Fuquay and Buettner [5] and Latimer [7], however, have both found that inverting the Eppley pyranometer results in a decrease in sensitivity of about 5 percent. With an uncorrected albedo of 80 percent, typical of Antarctic snow, a 5 percent error in the value of the reflected solar radiation will result in the true albedo being underestimated by about 4 percent. This possible error was sufficiently large to justify additional testing.

APPARATUS AND PROCEDURE

A check box was constructed consisting of a light-proof box approximately 18 in. square by 6 ft. tall. In the initial model of the box, the 1500-watt frosted lamp was located in the top compartment and one or two pyranometers in the bottom compartment, the two sections divided by a flat piece of flashed opal diffusing glass. The box was designed to rotate around its center. In the second model of the box, the lamp was relocated and placed in the center (on the axis of rotation) and pyranometers exposed at both ends, one behind the diffusing glass and the other open to the lamp. An externally mounted blower ventilated the lamp compartment and maintained a reasonably uniform temperature within the box. All interior surfaces were painted flat black. Photovoltaic cells and thermocouples were located in both the lamp and pyranometer compartments. The photocells were mounted in both horizontal and vertical positions to determine any variations in their outputs caused by inverting. None was noted. The lamp voltage was controlled in a manner identical to that used for the temperature tests.

TABLE 2.—*Inversion tests of Eppley pyranometers*

Instrument No.	Number of runs	Radiation intensity (ly./min.)	Response
3073	17	0.16 to 0.44	0.962±0.0045
3063	1	.41	.937
3041	1	.41	.936
2933	1	.40	.941
1950	4	.26 to .34	.953
873	4	.21 to .44	.942
1756	1	.34	.952
1718	1	.16	.958
4363	2	.26	.992
4365	2	.26 to .34	.988

The test procedure involved periodically rotating the box from an upright (pyranometer upright) to an inverted position. The box was kept in each position for 10 or 15 min. constant for each test run, with the run consisting of 3 to 6 stops at each position. Readings of all elements were made each 5 min. with a precision potentiometer.

TEST RESULTS

A large number of pyranometers was tested in order to detect variability, and Eppley No. 3073 was used in every run to check repeatability. Table 2 presents the results. These data confirm the findings of Fuquay and Buettner [5] and Latimer [7] and indicate a rather uniform decrease of 4 to 6 percent in sensitivity when the pyranometer is inverted. With the exception of instruments No. 1718 and 1756, which are 10-junction models (sensitivity near 2.5 mv./(ly. min.$^{-1}$)), all the pyranometers are high sensitivity models. The table includes results from two pyranometers of different design, No. 4363 and 4365. These are the double hemisphere, temperature-compensated instruments referred to earlier and described by Marchgraber and Armstrong [11]. It appears that these two instruments are less affected by inverting than the conventional bulb-type Eppley pyranometer. The two box configurations gave identical results although the second model with the lamp mounted on the axis of rotation provided better temperature control. There did not appear to be any relationship between radiation intensity and sensitivity reduction, as suggested by Fuquay and Buettner [5], over the range of 0.16 to 0.44 ly./min. The standard deviation for the 17 separate tests of Eppley No. 3073 was 0.0045.

5. PYRHELIOMETER CALIBRATION CHECKS

During interludes in the Antarctic radiation program, the normal incidence pyrheliometers were returned to the

TABLE 3.—*Pyrheliometer comparisons*

Instrument No.	Calibration constant (mv./(ly. min.⁻¹))	
	Eppley Lab.	Weather Bureau
2968	1.81	1.81
3546	1.98	2.00
3548	2.10	2.11
3551	1.98	1.98
3903	1.95	1.95

Weather Bureau in Washington, D.C., and compared against substandard Eppley No. 1330 maintained by Mr. T. H. MacDonald. The constant for No. 1330 was obtained by comparison with substandard No. 3289 which in turn had been compared with Silver Disc No. 78 in 1958–59. In addition, No. 1330 compared to within 0.001 ly./min. with Ångstrom No. 310 at Davos, Switzerland in March 1959.

The Weather Bureau comparisons were made on several clear days in June 1963. The results are presented in table 3. The Weather Bureau comparisons are in excellent agreement with those made at Eppley Laboratory and indicate good comparability between the Weather Bureau and Eppley standards.

At the South Pole in February and November 1964, two pyrheliometers were compared with the station pyrheliometer No. 3546. These comparisons were made to check the accuracy of the direct solar measurements made at the South Pole following the eruption of Mt. Agung, Bali and the subsequent dispersal of the resulting dust cloud over the world [4]. The results of these comparisons are presented in table 4.

All the values in table 4 were calculated with a temperature response of 100 percent. This was valid for No. 3546 from the laboratory tests, and from the close agreement in the South Pole comparisons, appears acceptable for No. 2968 and No. 2966 as well.

In this regard it may also be noted that the Eppley and Weather Bureau calibrations of No. 2968 reported in table 3 were made at 43° and 86° F. respectively and resulted in identical calibration constants.

6. PYRANOMETER CALIBRATION CHECKS

As a means of maintaining quality control of the Weather Bureau Antarctic radiation data, the stations carry out a program of routine field calibration checks.

TABLE 4.—*South Pole pyrheliometer comparisons*

Date	Temperature (°F.)	Radiation intensity (ly./min.)		
		No. 3546	No. 2968	No. 2966
Feb. 1, 1964	−32	0.920	0.901	
Feb. 17, 1964	−43	0.645	0.640	
Nov. 11–12, 1964 (5 comparisons)	−41	1.123		1.126

This consists, among other things, of periodic shade calibrations of the Eppley pyranometers using the Eppley normal incidence pyrheliometer as the substandard. The shade calibrations are performed during cloudless conditions by interposing a disk shade between the pyranometer and the sun so that the direct solar beam (and a small amount of circumsolar radiation) is screened from the instrument. The geometry of the system is controlled so that the disk shade subtends an angle at the pyranometer approximately equal to the aperture of the pyrheliometer, that is about 5.75°. This feature is important, particularly if the atmosphere is very turbid. Ångstrom [1] has indicated that a difference of 5° in the apertures of the two instruments being compared can cause a 4 percent difference in the amount of radiation received when the turbidity coefficient (β) is 0.15, a value typical of mid-latitude cloudless conditions. For accurate results, it is also important that the sky be cloud free since the calibrations require about 30 min. and any drifting cloud segment will have varying effects on the shaded and unshaded pyranometer readings.

The field calibrations are made by comparing the difference in the unshaded and shaded pyranometer readings with the vertical component of the direct solar radiation calculated from the pyrheliometer measurement, as follows:

$$K^*_{Dir} = \frac{\Delta}{R_t I_m \sin \alpha} \tag{1}$$

where

K^*_{Dir} = computed pyranometer calibration factor for direct radiation

Δ = unshaded minus shaded pyranometer output in millivolts

R_t = pyranometer temperature response

I_m = pyrheliometer measurement of the direct solar radiation on a normal surface in ly./min.

α = solar elevation (at the South Pole the solar declination).

SOUTH POLE SHADE CALIBRATIONS

The pyranometer calibrations discussed here were made at the South Pole station (Amundsen-Scott) during the period 1960–62. Because the station is at the geographic pole, the solar elevation varies only slowly with time, a distinct advantage when making shade calibrations. Under normal conditions, the Ångstrom turbidity coefficient, β, with clear skies at the Pole, is zero, based on measurements made by the first author. Since the temperature response of each pyranometer is known, errors in the shade calibrations will be caused by the instrument's cosine response, azimuthal variations, and inaccuracy of sensor level. Because of the small daily change of solar elevation, the combined effect of azimuth and instrument level error may be easily detected by noting the diurnal variation in pyranometer output on clear days. With care this effect can be reduced to ±1

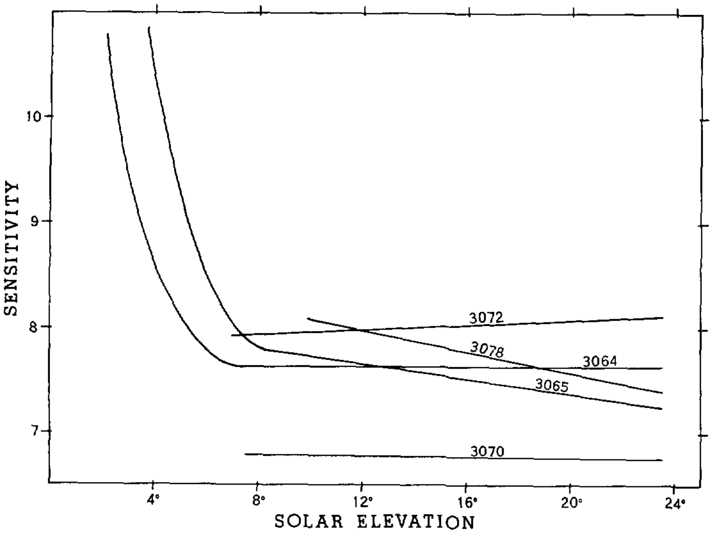

FIGURE 2.—Variation of pyranometer sensitivity (mv/(ly. min.$^{-1}$)) with solar elevation from Amundsen-Scott (South Pole) direct solar calibrations.

percent. With a large number of shade calibrations made at different times of the day, the combined azimuth and leveling error cancel out so that the major effect remaining is due to the instrument's departure from the Lambert cosine law (cosine response).

Figure 2 presents sensitivity curves for five Eppley pyranometers from shade calibrations made at the South Pole. The straight line portions of the curves between 8° and 23.5° solar elevation were obtained by the method of least squares and the curved portions fitted by eye. The shape of the curves for elevations less than 8° is inverse to that usually ascribed to Eppley pyranometers (see for example MacDonald [8]). This is the result of our use of astronomical tables to obtain the solar elevation rather than actually observing it, and consequently ignoring the obviously large effect of refraction at low sun angles. These segments of the curves for angles less than 8° are therefore not considered accurate and more work is required to obtain the true shape of the calibration curve in this region.

Table 5 compares the South Pole shade calibrations with laboratory calibrations made in the Weather Bureau's integrating sphere. Listed in the table are standard deviations (S.D.) from the regression curves of figure 2 which indicate that for three of the pyranometers the variation of the individual shade calibration was ±1 percent and for the other two it was ±2 percent. Because the integrating sphere uses diffuse illumination while the shade checks are made against the direct solar beam, the calibration factors obtained in the two methods are not necessarily comparable. With the exception of No. 3070, however, all the pyranometers show significant variation, ranging from −4 to +14 percent, between the shade and integrating sphere calibrations. It thus appears that the pyranometer sensitivity is different for diffuse radiation and beam radiation, probably because

TABLE 5.—*South Pole and integrating sphere pyranometer calibrations. The calibration constants have been corrected for temperature.*

Instrument No.	Number checks	South Pole shade calibrations (mv./(ly. min.$^{-1}$))				Integrating sphere calibrations (mv./(ly. min.$^{-1}$))
		S.D.	Solar elevation			
			23.5°	15°	8°	
3064	50	0.076	7.64	7.64	7.64	7.89
3065	57	.139	7.25	7.56	7.81	7.46
3070	76	.062	6.76	6.77	6.79	6.76
3072	62	.120	8.12	8.02	7.94	8.47
3078	50	.060	7.41	7.83	8.18	7.19

TABLE 6.—*South Pole pyranometer diffuse calibrations*

Instrument No.	Number hours compared	K^*_{Dif} (mv./(ly. min.$^{-1}$))	K^*_{Dif}/K_{IS}
3070 (substandard)		6.76	
3072	75.5	8.30	0.980
3064	11.5	7.73	0.980
3078	44.0	7.23	1.006

of the cosine response, and that the calibration factor used for total solar measurements should probably be a combination of the two factors weighted according to the actual amounts of diffuse and direct radiation. This is not an impractical suggestion if automatic data processing is available.

OTHER SOUTH POLE CHECKS

For extended periods during the 1961–62 summer at the South Pole, several Eppley pyranometers were exposed simultaneously. The resulting data provided additional information with which to study the comparability of Eppley pyranometers.

Periods of 10/10 opaque cloud cover when the direct radiation was zero, provided data to compare the diffuse calibration factors (integrating sphere factors) of the pyranometers. For comparison purposes, No. 3070 was selected as the substandard. Table 6 gives the results of these comparisons. K^*_{Dif} identifies the field determinations of the diffuse factor and K_{IS} the integrating sphere value.

By combining the calibration factor for direct radiation K^*_{Dir} represented by the regression curves of figure 2 with the diffuse factor K^*_{Dif} from table 6, a reduction factor K^* for total solar radiation may be written for each pyranometer as follows:

$$\text{No. 3070, } K^*=[(6.799-.00175\alpha)x+6.76y]R_t\approx 6.76\ R_t \quad (2)$$

$$\text{No. 3064, } K^*=(7.64x+7.73y)\ R_t \quad (3)$$

$$\text{No. 3065, } K^*=[(8.092-.03579\alpha)x+7.46y]\ R_t \quad (4)$$

$$\text{No. 3072, } K^*=[(7.840+.01209\alpha)x+8.30y]\ R_t \quad (5)$$

$$\text{No. 3078, } K^*=[(8.573-.04966\alpha)x+7.23y]\ R_t \quad (6)$$

where α=solar elevation, x=percent of direct radiation,

y=percent of diffuse radiation, R_t=pyranometer temperature response

The quantity x is obtained from measurements made with the pyrheliometer and y from measurements made with a pyranometer equipped with a permanent shade ring screening it from the direct solar radiation. In the absence of the diffuse pyranometer reading, y may be estimated from the direct solar measurement alone. For instruments having direct and diffuse factors nearly the same such as No. 3070 (and possibly No. 3064), it is practical to use a single factor.

Table 7 presents the results of simultaneous exposure comparisons using both the empirically determined reduction factor, K^*, according to equations (2) through (6), and the integrating sphere factor, K_{IS}. Pyranometer No. 3070 was the basis for the comparisons and the response values in the table were obtained by comparing the total radiation measured with the test pyranometer against the total radiation measured with No. 3070. Only complete days were used in the comparison, and all data have been corrected for temperature.

The data in table 7 indicate that simultaneous total solar measurements using the empirical reduction factor compare to approximately ± 1 percent, while the integrating sphere factor gives variations between instruments of approximately ± 3 percent. The difficulty that can be encountered using the integrating sphere calibration factor alone is illustrated by comparing instruments No. 3078 and No. 3064 for November 1961 where the measurements differ by 5.1 percent. At the South Pole, at least, where solar elevations are never greater than 23.5° it is obvious that a single calibration factor such as that provided by the integrating sphere is inadequate.

7. CONCLUSIONS

From our studies, as well as from previous work, it appears that comparable solar radiation measurements are possible only when the temperature and cosine response characteristics of the individual pyranometer are considered in the data reduction. Seasonal and latitudinal comparisons of uncorrected data collected with instruments of the same manufacture can be in error by as much as 10 to 15 percent. Comparability cannot be expected even when similar instruments are identically exposed if the integrating sphere calibration factor alone is used in the data reduction. The possible magnitude of the errors in uncorrected data is intolerable considering that the instrument characteristics responsible for the errors are easily determined and that the data reduction is simple with electronic computer assistance. A computer program for the reduction of Antarctic radiation data taking account of the known instrument characteristics is currently being developed in the Polar Meteorology Research Unit of ESSA.

TABLE 7.—*Total solar radiation using* K^* *and* K_{IS}

Instrument No.	Factor	Nov. 1961		Dec. 1961		Jan. 1962	
		Days	Response	Days	Response	Days	Response
3072	K^*			30	0.999	28	0.991
	K_{IS}				0.967		0.957
3078	K^*	20	0.984	16	0.988		
	K_{IS}		1.024		1.013		
3064	K^*	18	1.002	1	0.999		
	K_{IS}		0.973		0.967		
3065	K^*	5	0.998				
	K_{IS}		0.962				

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